DTU Library

Wind power in Denmark

Lemming, Jørgen Kjærgaard; Andersen, Per Dannemand; Madsen, Peter Hauge

Publication date:
1999

Document Version
Publisher's PDF, also known as Version of record

Energistyrelsen
Miljø- og Energiministeriet

Wind Power in Denmark
Technology, Policies and Results

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Energistyrelsen
Miljø- og Energiministeriet

Wind Power in Denmark
Technology, Policies and Results

Wind Power in Denmark

Technology, Policies and Results

Edited by
Per Dannemand Andersen, Risø National Laboratory

Financed by
Danish Energy Agency, Jour. no. 51171/97-0008

Layout and printing
Information Service Department, Risø, November 1998

Available through
Danish Energy Agency and Risø National Laboratory,
Information Service Department, P.O. Box 49, DK-4000 Roskilde, Denmark

Contents

1 Introduction

1.1 Early Use of Wind Power in Denmark

With no other natural energy sources (no waterfalls for hydropower, no coal, no known oil or gas resources, etc.), it was natural that Denmark should become one of the first countries in which scientists and engineers began a dedicated effort to implement wind technology as a basis for electrification. This started in 1891, when Poul la Cour and a team of scientists built a test windmill, funded by the Danish government, at Askov Folk High School. La Cour drew on the results of two contemporary Danish engineers and scientists, H. C. Vogt and J. Irminger, who together with the American scientist, P. S. Langley, participated in formulating the modern theory of aerodynamic lift and drag.

Figure 1. Siting of the more than 4800 turbines in Denmark. Source: Energi- & Miljødata.

Shortage of imported fossil fuels during World War I provided a powerful incentive for utilising wind energy for electricity production. By 1918, as a result of la Cour's work, a quarter (120) of all Danish rural power stations were using wind turbines for power generation. Most turbines had a rated capacity of 20-35 kW. After the war, with a sufficient supply of fossil fuels, these machines rapidly became outdated, and in 1920 only 75 turbines were left.

World War II also caused a shortage of imported fossil fuels, renewing interest in wind power. Towards the end of the inter-war period and during World War II, Danish industrial wind power development was undertaken by two companies in particular: Lykkegaard and F. L. Smidth & Co. A/S. By 1943, Lykkegaard had installed 90 turbines; most of them of the 30 kW type. F. L. Smidth & Co. developed two types: a 2-bladed 60 kW turbine and a 3-bladed 70 kW turbine. 21 of these were installed during World War II.

After World War II, the Organisation for European Economic Co-operation started to examine Europe's future access to fossil fuels on the international level. One of the results of these deliberations was the initiation in 1950 by the Association of Danish Electricity Utilities of an investigation of the possibilities of utilising wind power in the Danish electricity supply system. By the end of the war, J. Juul, a Danish engineer at the SEAS power utility embarked on an R&D programme on wind energy utilisation which was to form the basis for Juul's design of a modern electricity-producing wind turbine - the well-known 200 kW Gedser machine. The Gedser machine was installed in 1957 and was in operation until 1967. In 1977, when data for large wind turbines were needed, the refurbished Gedser turbine was used for a measurement programme.

The oil embargoes of 1973 and 1979 and the awakening green movements sat the stage for the present era of wind power. The oil embargoes, moreover, promoted exploration of the offshore oil and gas fields in the Danish part of the North Sea and a switch-over from oil based to coal based power generation. Today, Denmark is a net exporter of oil and gas, and most power is generated at coal-fired combined heat and power (CHP) plants. Furthermore, Denmark has some of the European Union's lowest fossil-fuel based power generation costs. As a consequence, security of supply and cost of energy

Table 1. Status for wind turbines in Denmark at the end of 1997. Status by in July 1998. Source: Danish Association of Electricity Utilities (DEF).

Owner type	Number of machines		Capacity in MW		Production in GWh	
	1996	1997	1996	1997	1996	1997
Utility	637	672	203	222	315	384
Private	3613	4112	639	902	912	1548
Total	4250	4784	842	1129	1227	1932

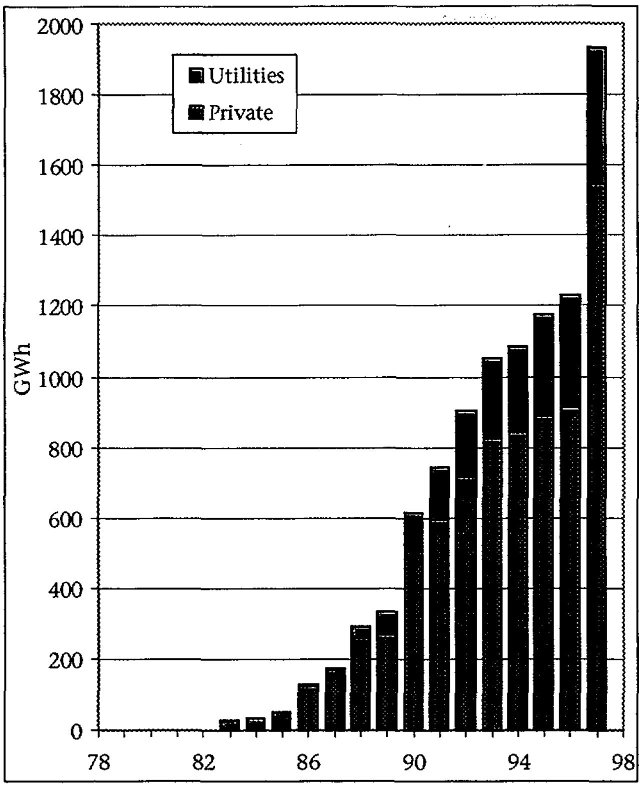


Figure 2. Electricity production from wind turbines. Source: Danish Association of Electricity Utilities (DEF).

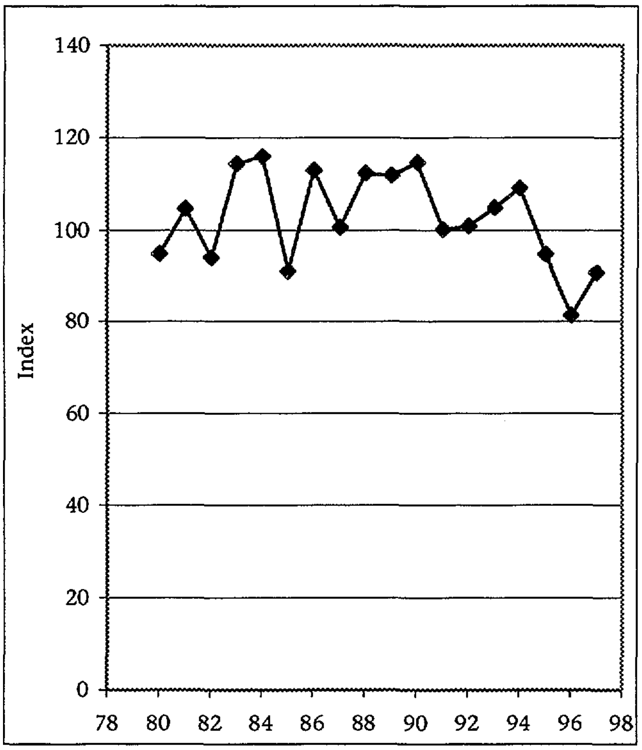


Figure 3. Index of the content of energy in wind Source: Naturlig Energi.

are not urgent political problems. However, Denmark has one of the highest per capita CO_2 emissions in the world, and the prospect of climate changes is the main reason for the present focus on wind energy utilisation.

1.2 Wind Power in Denmark Today

The Association of Danish Electricity Utilities has estimated the total electricity production from wind turbines in 1997 as 1932 GWh: 384 GWh from utility-owned turbines and 1548 GWh from privately owned turbines. This equals 6% of total electricity consumption in Denmark. Corrected to a "normal wind year" this equals 6.6% of Denmark's annual electricity con-sumption. The wind energy index in 1997 was 91%.

According to the Danish Association of Electricity Utilities, 4784 turbines with a capacity of 1129 MW were connected to the grid at the end of 1997. 534 turbines and 287 MW were added in 1997, the largest figure ever. These are net figures and included dismantled machines. The actual sales of turbines is a bit higher, reflecting the fact that not all machines sold in 1997 were installed that year. New machines are usually 500 kW, 600 kW and 750 kW. No 1500 kW machines have as yet been installed on a commercial basis in Denmark.

2 Wind Power in Danish Energy Policy

Denmark has a long tradition of implementing vigorous energy policies with broad political support and involving a broad range of actors: energy companies, industry, grass roots associations, municipalities, research institutions and consumers.

The aim of the first energy strategy, *Danish Energy Policy 1976*, was to safeguard Denmark during international energy crises such as those of 1973-74. The following plan, *Energy 81*, could go further, given the drastic price rises in energy following the embargoes in 1979-80; it also emphasised socio-economic and environmental considerations. After a period during which large-scale projects for facilities and markets for natural gas and combined heat and power generation were developed, the action plan, *Energy 2000*, followed in 1990, introducing the goal of sustainable development of the energy sector. *Denmark' Energy Futures*, a discussion paper published in December 1995, contains a technical analysis of future scenarios for energy consumption and supply in Denmark. It was followed and expanded by *Energy 21*, the fourth of the energy strategies, which lays down the energy-policy agenda for the years to come.

Development and implementation of wind energy have been included in all four energy strategies. Both demand pull-policy instruments (financial and other incentives) and technology push-policy instruments (certification schemes and R&D programmes) have been used as tools in these strategies.

2.1 Wind Energy in Energy 21

In 1996 the Danish Government's new Plan of Action - *Energy 21* - was published. One important issue in *Energy 21* was that the Government set a national target for reducing CO_2. By 2005, Denmark will fulfil its international obligations by reducing total Danish CO_2 emissions into the atmosphere by 20% from their 1988 levels. In the longer term Denmark is willing to accept the reduction targets that follow from the conclusions of the International Panel on Climate Change. Should this be decided, Denmark and other highly-developed industrial countries with high CO_2 emissions would strive to reduce their CO_2 emissions to half their 1990 levels by 2030. A condition for the Government's decision to aim at halving CO_2 emissions before 2030 is that international efforts in both technological development and design of market conditions and mechanisms support this Danish endeavour.

In arriving at these reduction targets, renewable energy and wind energy play an important role. In Energy 21 the government estimates that domestic renewable sources of energy will contribute some 12-14% (100 PJ) of total gross energy consumption by 2005. It is also estimated that renewable energy will increase its share of the energy supply to about 35% (235 PJ).

Today, the most recent large wind turbines are so competitive that using electricity from wind turbines is one of the cheapest ways of reducing CO_2 emission from power production.

As a result of the actions taken in Energy 21 the Government estimated that 1500 MW of wind turbines will be installed by the year 2005, corresponding to 12% of electricity consumption. Because the installation of wind turbines has taken place more quickly than anticipated, this will have been achieved before the year 2000. In the long term, the Government is expecting 5,500 MW wind power by 2030 (of which 4,000 MW is expected to be sited offshore) corresponding to 50% of electricity consumption.

Total power production from the 1,500 MW will be approx. 3.3 TWh corresponding to reducing CO_2 emission by 2.8 million tons. By way of comparison, the country's total CO_2 emission was 58.6 million tons in 1996. The 1500 MW of wind power provides one quarter of the national target of a 20% reduction of the CO_2 emissions by 2005.

The most economical way is still to erect wind turbines on land. But area resources on land are limited when housing, nature, and landscape considerations are to be taken into account. Furthermore, wind conditions at sea are considerably better than at sites on land, and wind turbines erected offshore are expected to become competitive in step with the development of technology.

The Government expects that a significant part of the expansion until 2005 will take place on land. As wind turbines become larger and hence more difficult to place in landscapes, the number of new sites will be limited. The increase of wind turbine capacity on land after 2005 will have to be effected, among other things, by renovation of wind turbine areas as well as by removal or replacement of existing wind turbines in accordance with regional and municipal planning. In the longer term the main part of new development will take place offshore.

In order to provide individual households outside areas with district heating and natural gas supplies with better opportunities to contribute to the use of cleaner energy, the Government has supported the development of small wind turbines (household turbines) producing electricity for heat and power. The small wind turbines are seen as a supplement to the general development of wind power.

Table 2. Policy instruments used to promote wind-turbine technology and installations.

Demand pull instruments	Technology push instruments
Incentives	Incentives
• Direct subsidies	• R&D programmes
• Taxation	• Programme for household turbines
• Replacement of small and old turbines	• Test station for wind turbines
• Aid programmes	• International co-operation
Other regulation	Other regulation
• Resource assessment	• Approval scheme
• Local ownership	• Standardisation
• Agreements with utilities	
• Regulation of grid connection	
• Electricity purchase arrangements	
• Information programmes	
• Spatial planning procedures	

3 Regulatory Conditions for Wind Power in Denmark

From the very first policies in the late 1970s, both demand pull instruments and technology push instruments have been used. Different forms of direct subsidies and regulatory incentives have been implemented.

3.1 Ownership of Wind Turbines

Different groups own wind turbines: private individuals, private co-operatives and electricity utilities. In addition, wind turbines are owned by a few private industrial enterprises and municipalities.

3.1.1 Private Involvement

Private enthusiasm and entrepreneurship have played a very important role in developing wind power utilisation in Denmark. When the first wind turbines were in stalled in Denmark in the early 1970s, it was not due to governmental programmes and subsidies but to the enthusiasm of private individuals and their willingness to take risks.

Because private enthusiasm has been a driving force in the development of wind power in Denmark, local private ownership of wind turbines has been promoted politically by the Government and the Parliament. Another reason is that the environmental advantages of wind power are on the global or national level, whereas its environmental disadvantages are on the local or neighbourhood level, associated with the presence and operation of wind turbines. Such local disadvantages can lead to a lack of public acceptance of wind farms. Local ownership of wind turbines (i.e. allowing local farmers, co-operatives or companies to benefit from the wind turbines) can ensure local acceptance of projects. In particular, co-operatives spreading ownership of a wind turbine between 20 to 100 families in the vicinity of the wind turbine has been stimulated.

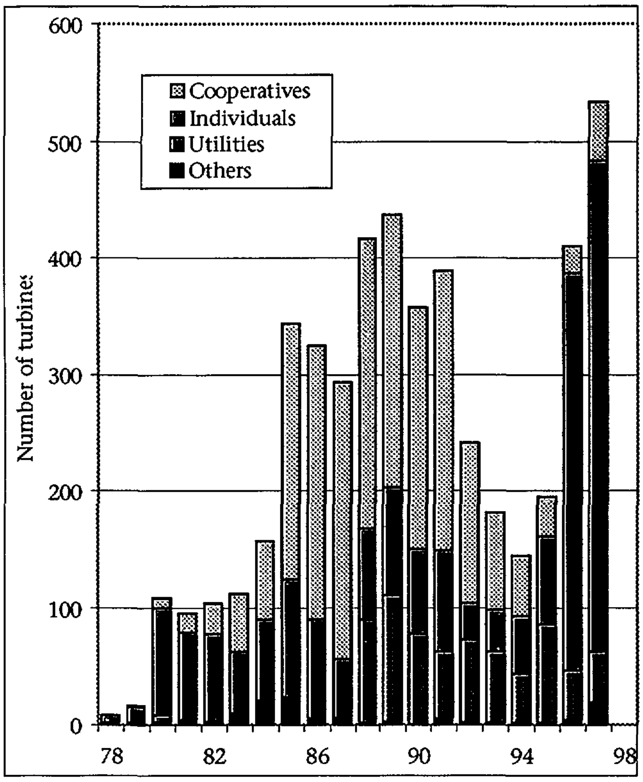


Figure 4. Annual installations (in number of machines) of wind turbines, by types of owner. Source: Energi- & Miljødata for the Danish Energy Agency.

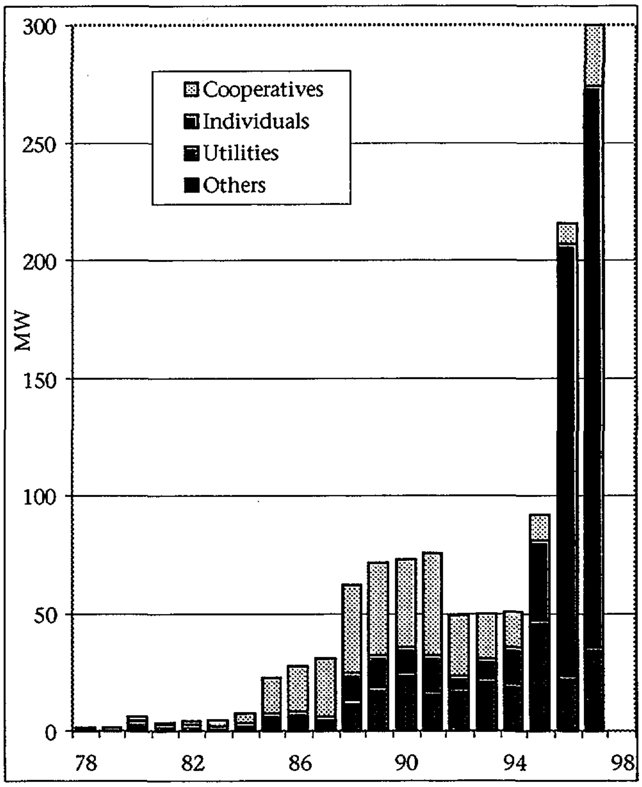


Figure 5. Annual installations (in rated capacity) of wind turbines, by types of owner. Source: Energi- & Miljødata for the Danish Energy Agency.

During the 1980s and early 1990s most new turbines were installed by co-operatives. Since the mid 1990s it is primarily farmers who have installed individually owned wind turbines. This development is due to several factors: general interest rates have decreased, payment for wind power electricity has increased slightly, and wind turbines have become less expensive.

3.1.2 Utility Involvement

Danish utilities have been involved in wind power utilisation from the beginning. As early as the 1950s SEAS, a privately owned electricity utility, experimented with wind turbines. When the first wind power programme was initiated in the 1970s, Danish electricity utilities participated in the utility scale research programme.

In 1985 an agreement was reached between the Government and the Danish electricity utilities, committing the utilities to install 100 MW of wind turbines over a five-year period. This agreement was fully implemented by the end of 1992. A second 100 MW agreement between Government and utilities, entered in 1990, was finally implemented in 1996. According to an Executive Order from the Government, a third utility phase of an additional 200 MW is to be installed by 2000. These three phases have primarily focused on land-based wind turbines, but the two offshore 5 MW demonstration wind farms, Vindeby and Tunø Knob, are also results of the agreements between the Government and the utilities.

On 29 September 1997 Svend Auken, Minister for Energy and Environment, published an agreement with the Danish utilities to develop 750 MW more offshore wind power by the year 2008. The 750 MW is assumed to be installed in five wind farms. Together, these five wind farms will produce 8% of Denmark's consumption of electricity. This was the starting point for large-scale offshore wind farm development in Denmark.

3.2 Financial Incentives

3.2.1 Direct Subsidies

In 1979 the Government introduced a renewable energy programme that included installation and production subsidies. An installation subsidy of 30% of total project costs was granted to wind turbines. As the industry matured and wind turbine prices started to decrease, the installation subsidy was gradually reduced until it was finally abolished in 1989. A total of 2567 turbines received installation subsidies of DKK 275.72 million in current prices between 1979 and 1989.

Direct production subsidies have continued to be granted in different versions over the years. Today, a production subsidy of DKK 0.27/kWh is granted to private wind-turbine owners. There are limitations on the wind-farm developments to which the above incentives apply. Private individuals, for example, are only allowed to grid-connect one turbine, and this must be placed on the owner's land. Similarly, each shareholder in private co-operatives is limited to owning shares equal to 30.000 kWh. The shareholders must live in the same municipality as where the turbine is installed.

Power utilities receive DKK 0.10/kWh in subsidy as reimbursement of the general CO_2 tax on electricity. This is handled in the same way as the DKK 0.27/kWh subsidy to privately owned turbines.

If any significant improvement of the return on investment in wind energy should occur (lower interest rates, cheaper wind turbines, higher general electricity tariffs), the Government will probably consider changing the production subsidy.

3.2.2 Taxation

Favourable taxation schemes have been utilised to stimulate private wind turbine installations. These taxation schemes have changed over time. Today, income from wind turbines by and large is taxed like other income.

Private persons and companies can chose between two models for taxation of their income from wind turbines or shares in wind turbines. For owners of turbines acquired before the present taxation rules, a number of other rules exist.

Owners of individually-owned or company-owned turbines often chose to pay income tax in the same way as income from other investments, i.e. full tax on the income but with deductions for the annual depreciation of the investment and expenditures on operations and maintenance costs, according to the usual tax regulation.

Shareholders in private co-operatives can chose a "simplified model", according to which the first DKK 3000 of income from sale of wind power is tax free and 60 % of the rest is taxed with the usual marginal income tax percentage: usually more than 60%. No deductions are allowed. The simplified income-tax model provides a tax incentive for owners of small shares in a wind turbine. The smaller the share, the larger the relative incentive. This is used as an instrument to spread the ownership of wind turbines to as many citizens as possible.

3.3 Utility and Grid-Related Issues

3.3.1 Electricity Production

Denmark has relatively few electricity-and energy-intensive industries nor is domestic heating usually based on electrical power. Denmark has no tradition of governmental owned electricity utilities: the ownership of the electricity utilities is quite heterogeneous. Some are owned by cities and municipalities, some by co-operatives and some by private shareholders. Restructuring of the sector has been initiated. By 1 January 1998 the western part of the ELSAM utilities was divided into a production company, ELSAM, and a grid operator, I/S Eltra.

Total electricity production capacity (excluding wind turbines) was 9,544 MW by the end of 1997and net sale of electricity in 1997 was 32,356 GWh. A large part of Denmark's electricity is produced in combined heat and power plants (CHP).

3.3.2 Tariffs

In 1997 the average price of electricity from power distribution utilities varied from DKK 0.295 to 0.442/kWh. For private consumers (connected to the 400/230-Volt distribution grid), a number of taxes are added to this price. The electricity tax was DKK 0.40/kWh in 1997 increasing to DKK 0.46/kWh in 1998. The CO_2 tax is DKK 0.10/kWh. The SO_2 tax is DKK 0.009/kWh. On top of this, 25% VAT is added. In 1997 the average consumer price for Danish low-voltage customers was between DKK 1.0/kWh and DKK 1.2/kWh. See Figure 6.

3.3.3 Payment for Wind-Generated Electricity

The utilities are obliged by law to receive and pay for wind-generated electricity from private producers and different arrangements have existed over the years. Since 1993 the payment for wind-generated electricity has been related to the utilities' production and distribution costs (tariffs). A law obliges power utilities to pay wind turbine owners a kWh rate of 85% of the utility's production and distribution costs (85% of DKK 0.38/kWh in 1997). As mentioned above, the Government reimburses wind-turbine owners the DKK 0.10/kWh CO_2 tax and adds DKK 0.17/kWh in direct subsidy. As a result, in 1997 the average selling price of wind-turbine owners was approximately DKK 0.6/kWh.

3.3.4 Grid Connection Costs

In accordance with an Executive Order, the costs of grid connection of wind turbines are split between the owner of the wind turbine and the electricity utility. The wind-turbine owner must bear the costs of the low voltage transformer and connection to the nearest connection point on the 10/20 kV distribution grid, while utilities must carry the costs for reinforcement of the 10/20 kV distribution grid when such is needed.

The connection point is usually the closest distance between the turbine and the grid, although the distribution company has the right to reject the connection if it can prove that it will become very expensive and no other plans exist (i.e. a municipal plan) in the area for other installations in the future. In this case, the utility has to present another solution.

Single wind turbines are usually connected to the 10 kV grid, whereas wind farms are often connected to the closest 10/60 kV transformer. In several cases, clusters of only 3 turbines have their own 10 kV line to a 10/60 kV transformer.

3.4 Spatial Planning Legislation

Spatial planning establishes a framework for siting wind turbines in the open land, and balances the interest of wind energy against other interests, including the way in which existing urban features and landscapes can best be protected. Tasks relating to environmental protection are increasingly integrated in the work of spatial planning. Spatial planning in Denmark is carried out at three levels: local and municipal planning in the municipalities, regional planning in the counties and national planning,

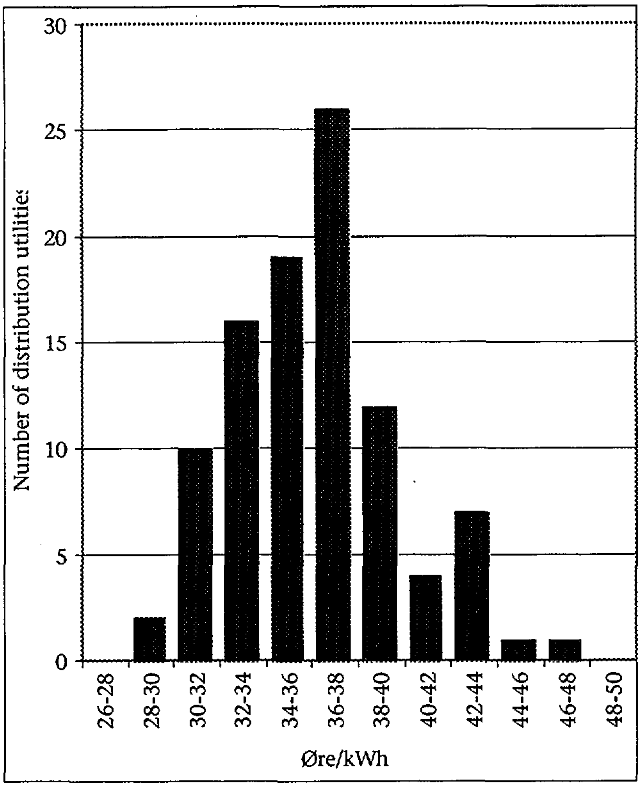


Figure 6. Denmark has 98 electricity distribution utilities. Each one has its own electricity price. The average in 1997 was DKK 0.38/kWh – not weighted with size of each utility. 1 DKK = 100 øre. Source: DEF.

co-ordinated by the Ministry of Environment and Energy.

The Ministry can influence planning through regulation, national planning directives and the dissemination of information. The location of wind turbines and high-voltage transmission lines in rural landscapes are two examples of areas where the Spatial Planning Department influences planning.

Counties issue zoning permits and installation permits in pursuance of the Act on Spatial Planning. All counties have prepared guidelines for regional planning which lay down the overall conditions for wind turbine deployment in each particular region/county.

Municipalities (the local planning authority) prepare local wind-turbine plans. Typically, these plans prescribe where turbines are to be installed and how (individual machines, clusters, parks), tower type and colour and distances to roads, dwellings, etc.

Decisions made by planning authorities can be appealed to the Nature Protection Board of Appeal, an independent body under the Minister of Environment and Energy.

3.5 Environmental Protection Legislation

Previously, installation of land-based wind turbines required no specific environmental assessment. The balancing of the interests of wind-energy utilisation against other interests in the open land was usually contained in the legislation on each area. Today, environmental assessments are more often required for wind farms and clusters of wind turbines.

Noise emission is one example. The noise emission of a wind turbine must be verified according to the rules in Ministry of Environment and Energy Executive Order no. 304. According to this, noise from wind turbines must not exceed 45 dB(A) outdoors at the nearest habitation in rural areas and 40 dB(A) in residential areas and other noise-sensitive areas. A simple method for calculating the noise emission of a wind turbine is specified in the Executive Order.

3.6 Building Legislation

The installation of wind turbines does not presuppose permission in terms of building codes. The rules in this legislative complex are assumed to be comprised by a type approval.

3.7 Replacement of Old Wind Turbines

In 1994 the Government introduced a three-year replacement programme for old and/or malplaced wind turbines. The replacement programme had two objectives.

First, replacement of existing, old small turbines (usually 55 kW machines) by new large ones (usually 600 kW) would increase the total potential of wind power resources. An investigation carried out for the Danish Energy Agency concluded that replacement of turbines up to a size of 75 kW would increase the resource potential by between 150 and 250 MW. Including sizes up to 130 kW would add another 117 MW to this potential.

Second, the first generations of wind turbines were often sited with no official planning and zoning restrictions. These turbines were often located in areas where wind-power utilisation is restricted today, for example, nature reservation areas or near residual areas. In addition, some older turbines are noisier than modern ones, and noise gives rise to public disapproval. By replacing such turbines with new ones on more suitable sites, some public disapproval can be mitigated. As a spin-off effect, the replacement programme could relieve pioneer wind turbine owners financially.

Over the programme period, only DKK 5.6 million was used on subsidies. 36 machines have been replaced by 31 new ones. The subsidy scheme has not been sufficiently attractive and other measures are being considered.

Turbines have been taken down for reasons other than the replacement programme. In 1998 the wind farm of Syltholm owned by the electricity utility, SEAS, was replaced. 24 400 kW turbines installed in 1988 were replaced by 25 new 750 kW turbines. No subsidy or public incentive was involved in this replacement.

3.8 Certification

The Danish approval scheme for wind turbines has been established to fulfil a common desire expressed by wind-turbine manufacturers, owners and authorities for a coherent set of rules for approval of turbines installed in Denmark. An approval is partly based on a type approval of the turbine and partly on a certified quality system which, as a minimum, describes the production and installation of the turbine. Today all manufacturers have an ISO9000 quality system.

A set of rules have been developed and adopted in "Teknisk Grundlag for Typegodkendelse og Certificering af Vindmøller i Danmark" (Technical Criteria for Type Approval and Certification of Wind Turbines in Denmark). Several recommendations are affiliated to the Technical Criteria:

- A recommendation for fulfilling the demands in the Technical Criteria (general recommendation)
- A recommendation for Basic Tests
- A recommendation for Power Curve Measurements
- A recommendation for Foundations

In the future the recommendations are to be replaced by IEC or CENELEC standards, and the Technical Criteria are to be harmonised on a European level.

Since 1979, Risø has been authorised by the Danish Energy Agency to issue licenses or type-approvals for wind turbines, including the tests and measurements required for the approvals. Today the market for these services has been liberalised, and private enterprises can be authorised to perform type approvals, certifications and tests and measurements. This market is open to international competition and several foreign enterprises are active. See the table below.

3.8.1 Type approvals

Type approval is recommended for wind-turbine types in serial production. Type approval is a verification of the wind turbine design according to an approval scheme. This scheme may be extended to cover specific national requirements.

The Danish scheme for type-approvals defines three approval classes: A, B and C.

To obtain an A-Type-approval there must exist a production certificate and an installation certificate. For A-Type-approval, loads and strength/service life must be documented for all load-carrying components. The documentation must be in the form of calculations or calculations and measurements. Outstanding items are not allowed in an A-Type Approval.

To obtain a B-Type Approval, production and installation certificates are required. The safety requirements are the same as for an A-Type Approval. But for a B-Approval items judged to have no essential influence on primary safety may be listed as outstanding items to be documented after the approval is issued.

C-Approvals are used for test and demonstration wind turbines in connection with development of a new wind turbine type - and in special cases for renovation of old wind turbines in connection with tests. C-Approvals are issued based on documentation of the safety aspects of the wind turbine. Quality and energy aspects are not verified. C-Approvals are time limited, normally to 3 years.

3.8.2 Administration of the approval scheme

Danish Energy Agency. The Danish Energy Agency is responsible for the administration of the approval scheme.

Advisory Committee. To assist the Danish Energy Agency, an advisory committee has been formed with representatives from the Danish Wind Turbine Manufacturers Association, the Danish Wind Turbine Owners Association, insurance companies and the electricity utilities.

Technical Committees. For discussion of technical and administrative matters regarding the approval scheme, a technical committee has been formed consisting of the authorised bodies. As several authorised bodies are non-Danish enterprises, the meetings of the technical committee are held in English. Minutes and other communications from the committee are primarily distributed in Danish. A separate technical committee has been set up for household turbines.

3.9 R&D Programmes

3.9.1 Overview

According to a recent OECD/IEA survey, a total of USD 2363 million has been spent on wind-energy related R&D from 1976 to 1995 of which Danish Government programmes amount to USD 100 million. That represents 4.2 % of the total efforts in the world during the

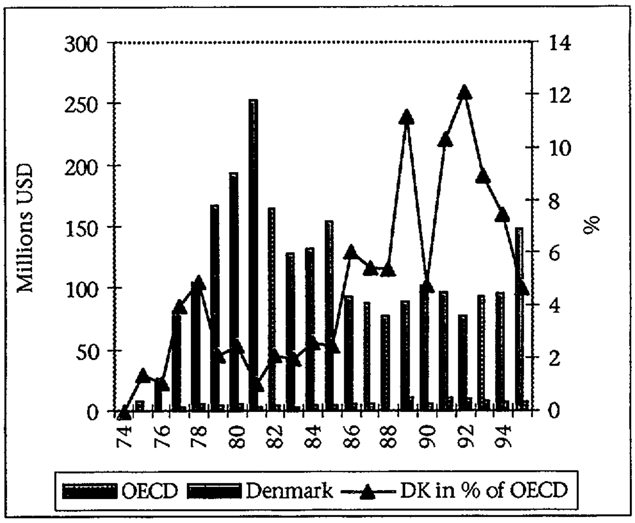


Figure 7. Government budgets for wind-energy related R&D in the IEA/OECD countries 1974 – 1995.1995 price level. Source: IEA Energy Technology R&D Statistics 1974 – 1995, OECD, Paris 1997.

Table 3. Bodies authorised by the Danish Energy Agency to provide services under the Danish scheme for certification and type-approvals for wind turbines.

Service	Authorised body
Production and installation certification	Dansk Standard Germanischer Lloyds Certification GmbH Det Norske Veritas Certification of Mgt. Systems Bureau Veritas Quality Insurance
Type approvals	Risø, Approval Secretariat Germanischer Lloyds
Basic tests	Risø, Test & Measurements Tripod Consult Aps
Power curve measurement	Risø, Test & Measurements Tripod Consult Aps DEWI, Wilhemshafen WindTest, Kaiser-Wilhelms-Kog GmbH
Noise measurement	DELTA Akustik & Vibration + bodies approved by DELTA DEWI, Wilhemshafen WindTest, Kaiser-Wilhelms-Kog GmbH Wind Consult GmbH

period. Compared to most other countries, Denmark has had relatively stable budgets for wind energy R&D.

The Danish Government has sponsored several R&D programmes on wind energy over the years. Today, government-sponsored R&D on wind energy comprises two programmes: the Energy Research Programme (EFP) and the Renewable Energy Development Programme (UVE). As a part of the latter, the Danish Energy Agency partly finances the Test Station for Wind Turbines at Risø National Laboratory.

3.9.2 Research programme – EFP

The first wind energy research projects were initiated and financed by the former Ministry of Trade (EM 1 and EM 2). For example, the two Nibe turbines and the establishment of the Test Station for Wind Turbines at Risø National Laboratory were results of these projects. Based on experience from these projects the Energy Research Programme (the EFP programme) has financed wind-energy related research projects since 1980. At the beginning, two lines existed within the research programme for wind power. One line was the research programme of the electricity utilities and the Danish Energy Agency focusing on large-scale wind turbines. The other line focused on small-scale wind turbines, and financed the research section of the Test Station for Small Wind Turbines, as the Test Station was named during its first years. The two lines were merged in 1989.

The Ministry of Environment and Energy Energy Research Programme (EFP) covers several technology areas, one being wind-energy technology. The Advisory Council on Energy Research (REFU) advises the Ministry of Environment and Energy and its Energy Agency. This REFU plays a key role in the overall strategic planning of the programme and it advises on the relative priorities between the programme areas.

For each programme area, REFU and the Energy Agency are advised by a Research Committee which represents a source of experience and technical competence within their fields of interest. The main role of the Research Committee is to develop detailed work plans and strategies against which individual projects can be assessed prior to initiation. Shareholders holders from the wind-turbine industry, wind-turbine owners, utilities, research, etc. have seats on the Research Committee for Wind Energy.

The Energy Agency administers the programme. Practically all projects within the wind energy area are initiated through the annual call for proposals issued by the Advisory Committee on Wind Energy; the deadline for project proposals is normally at the beginning of September. Projects normally run over two or three years and funding will be given by the end of each year. Almost all projects have several partners and industrial participation and co-financing is encouraged. The Danish Energy Agency typically finances 50% to 85% of the total costs. In the 1997 round (processed in 1996), five projects were supported with a total amount of DKK 13.35 million. In the 1998 round (processed in 1997) of the energy research programme (EFP), nine projects were initiated with a total of DKK 14.15 million in support from the Danish Energy Agency.

Project titles in the 1998 round of the research programme were:

- Rotor investigation (Vestas)
- Programme for research in aeroelastics 98-99 (Risø)
- Determination of dampening of edge-wise vibrations (Risø)
- Investigation of wind climates in connection with double stall on blades (ElsamProjekt)
- Validity of the assumption of Gaussian Turbulence (Risø)
- The numerical wind atlas – the KAMM/WAsP method (Risø)
- Power Quality and grid-connection of wind farms on weak grids (Risø)
- Direct current connection of wind farms (Elsam)
- Simplified connections of offshore wind turbine foundations (LIC-Consult)

3.9.3 Development Programme - UVE

The Development Programme for Renewable Energy (the UVE programme) was established in 1982 under the Danish Technology Board (Danish Industry and Trade Agency) and as per January 1 1990 the programme was transferred to the Danish Energy Agency under the Ministry of Environment and Energy.

The Advisory Council on Energy and Environment (Energy Environment Council) advises the Ministry of Environment and Energy and the Energy Agency. The Energy Environment Council has a more political role than the Advisory Council on Energy Research and its members are more active in public debate on renewable energy.

The same Technical Advisory Committees advise the ministry and the Energy Agency for the programme area of wind energy as under the research programme (EFP). This ensures efficient co-ordination of the activities within the two programmes.

Thus far, the programme has been renewed every three years. In the present period projects are initiated through a standing call for proposals. There is no deadline for project proposals, but they are discussed at the regular meetings of the Technical Advisory Committee. Projects are always shorter than three years. The typical total budget for wind-energy related projects has been between DKK 8 and 10 million in recent years. In 1997 an extraordinary, large budget was available and the Da-

Table 4. Budgets for Danish Government R&D activities. Current prices. Figures for research programmes (EFP) in 1981-1997 are budgets. The rest of the figures are based on budgets. Sources: Current issues of the Danish Energy Agency's annual report on the Energy Research Programme, Status og Perspektiver for Vindkraftudbygningen i Danmark, Danish Energy Agency, December 1991. Test Station for Wind Turbines annual agreements.

Year	Research programme EFP	Development programme UVE	Test Station at Risø
1976-79	28.700		N/A.
1980	6.600		N/A.
1981	9.990		N/A.
1982	17.150		N/A.
1983	17.100		N/A.
1984	13.000		N/A.
1985	16.365		N/A.
1986	12.600	38.600	3.673
1987	10.505		3.832
1988	11.435		4.629
1989	9.000		8.510
1990	9.910		8.758
1991	9.000	7.539	10.500
1992	9.585	11.895	11.468
1993	9.350	15.640	10.481
1994	9.336	14.942	8.600
1995	12.300	8.749	7.900
1996	14.915	6.338	7.500
1997	13.350	26.763	7.900

nish Energy Agency supported 37 projects during with a total of DKK 26.67 million.

The overall aims of the wind section of the renewable energy development programme are:

- To promote the technical potential for utilising wind power in Denmark through research, development and demonstration of new, improved wind power technology.
- To support the optimum utilisation of the available sites.
- To participate in removing barriers to sustainable utilisation of wind energy.
- To enhance the Danish contribution in international co-operation.
- To stimulate Danish industrial development and export.

3.9.4 Test Station for Wind Turbines

The Danish Energy Agency operates test stations for different renewable energy technologies as part of the UVE programme. One is the Test Station for Wind Turbines, established at Risø National Laboratory in 1978. At the beginning it was financed as a three-year project under the Energy Research Programme. The Test Station has subsequently received an annual budget through the development programme and it has submitted proposals to the EFP programme on an equal basis with other institutions. The figures listed in table 5 are budgets for the test station activities alone and not additional budgets for R&D activities, which are included in the EFP and UVE programmes.

The activities and the budget of the Test Station for Wind Turbine are negotiated each year. In 1997 the Test Station budget was DKK 7.9 million, and the activities comprised:

- Information activities
- Ad hoc assistance to the Danish Energy Agency
- International co-operation with other test stations for wind turbines
- Secretariat for the Danish certification and type-approval scheme
- Spot-check of type-approved turbines
- Inspections of major break-down of turbines
- International standardisation
- Development of test methods for wind turbines
- Development of test methods for blades
- Participation on the IEA annex on Round Robin test of a wind turbine.

3.9.5 Other Programmes and Projects

The programme entitled *New Energy Technologies* (Nye Energiteknologier) was established in 1980 with the aim of stimulating ongoing commercial manufacturing of new energy technologies. The budgets were used on industrial development projects and, in a few cases, as capital in new companies (e.g. the Danish Wind Technology company). Between 1980 and 1990 the Danish wind turbine industries received approximately DKK 42 million from this programme.

Between 1982 and 1989, the *Individual Energy Projects* (Energiøkonomiske enkeltprojekter) programme supported a number of demonstration wind farms, such as Masnedø (3.8 MW), Lynæs (0.9 MW), Oddesund Nord (1.1 MW), Ebeltoft (0.1 MW) and Tønder (0.7 MW for training purposes). DKK 24 million was granted in 1982-85 and DKK 2 million in 1986-89.

In addition to these programmes, the Danish Energy Agency has initiated a number of individual projects on wind-energy economy, project evaluation, etc.

3.9.6 International R&D Co-operation

International co-operation on wind-energy R&D is emphasised by the Danish Energy Agency. Denmark has participated in international co-operation in IEA R&D Wind since its establishment.

Danish universities, research centres, power utilities and the manufacturing industry participate in the European Union RTD programmes. No quantitative data are available.

Active Danish participation in international standardisation in the IEC and CEN/CENELEC is highly prioritised in the plan of action of the Danish Energy Agency on wind-energy R&D, and R&D efforts supporting international standardisation are encouraged.

3.9.7 Database on R&D Projects

All projects from the EFP and the UVE programmes are listed in a database available via the Internet: *Nordic Energy Index*. The database comprises an abstract, information on project management, budget, project participants, list of available reports, etc. The database is organised under the Nordic Council covering similar information from Norway, Finland and Sweden. The address is *www.risoe.dk/nei*. A search guide is available on the Danish Energy Agency's server: *www.ens.dk/forskning/nei_tips.htm*.

4 Organisations in the Wind-Energy Area

There is no "Danish Wind Energy Association". Wind turbine owners and wind turbine manufacturers have each formed an association to represent them.

The Danish Wind Turbine Owners Association was established in May 1978 and had 10,570 members at the end of 1997. Among its members are both wind-turbine owners and people with a general interest in promoting wind energy. Since 1979 the association's member magazine "Naturlig Energi" has been published each month. "Naturlig Energi" contains energy-policy debates, statistics on production and failures from 2,619 turbines (574.5 MW), an annual rating of consumer satisfaction with wind-turbine manufacturers, and news stories. "Naturlig Energi" has made the Danish wind-turbine market very transparent and facilitated efficient competition between manufacturers. The association represents private wind-turbine owners in negotiations with the government, utilities, insurance companies, etc. The association employs several wind-energy consultants available to advise wind-turbine owners and others on wind resource assessments, financial and taxation matters, etc. The association carries out information activities for promoting wind energy. Activities such as statistics and general information activities are partly financed by the Danish Energy Agency. As subsections of the association, a number of "manufacturer-groups" (a group for Bonus, a group for Vestas, etc.) exchange experience and participate in discussions with "their" manufacturer if needed. The organisation's web address is: *www.danmarks-vindmoelleforening.dk*.

The Danish Wind Turbine Manufacturers Association (DWTMA) was established in 1981. By the end of 1997, DWTMA had six A-members (Bonus Energy A/S, LM Glasfiber A/S, NEG Micon A/S, Nordex A/S, Vestas Wind Systems A/S, Wind World af 1997 A/S), 25 B-members (major component and service suppliers) and 39 C-members (small suppliers, consultants and service companies). The association publishes information about wind energy and it is engaged in energy-policy issues, economics, and standardisation. DWTMA has established a comprehensive web-site: *www.windpower.dk*.

5 Wind Power Economics

Today, wind energy is commercially competitive at specific sites with favourable wind conditions. If external/social costs are included, it is estimated that wind power already is competitive with fossil-fuel based power.

5.1 Cost of Wind Turbines and Projects

The ex-works cost of wind turbines has decreased significantly with the latest 600 generation kW (43 - 44 meter rotor diameter). For 600 kW machines installed in 1996 and 1997, the ex-works cost was, typically, DKK 3.15 million.

Additional costs depend on local circumstances, such as the condition of the soil, road conditions, proximity to electrical grid sub-stations, etc. Additional costs at typical sites can be estimated as 20% of total project costs for the 500 kW to 750 kW generation machines. Only the cost of land has increased during recent years.

The figures in table 5 are the result of a statistical analysis of a number of projects of 600 kW wind-turbine technology. The turbines in the analysis were sited individually or in clusters of up to 8 machines. See also figure 15 and 16.

5.2 Operation Costs

The technical life time or design lifetime for modern Danish turbines is typically 20 years. Individual components are replaced or renewed at shorter intervals. Consumables such as oil in the gearbox, braking clutches, etc. are often replaced at intervals of 1 to 3 years. Parts of the yaw system may be replaced at intervals of 5 years. Vital components exposed to fatigue loads (such as main bearings and bearings in the gearbox) might be replaced

Table 5. Cost and standard deviation of typical 600 kW wind-turbine projects. Based on a statistical analysis. Source: Risø National Laboratory.

Component	Average DKK	St. dev. DKK
Turbine ex-works	3,146,000	161,000
Foundation	149,000	20,000
Grid connection	288,000	70,000
Electrical installations	20,000	13,000
Tele communication	14,000	9,000
Land	103,000	84,000
Roads	39,000	44,000
Consulting	36,000	49,000
Finance	20,000	27,000
Insurance	94,000	53,000
Total	3,909,000	

halfway through the total design lifetime. This is dealt with as re-investment.

Operation and maintenance costs include service, consumables, repair, insurance, administration, lease of site, etc. Risø National Laboratory has developed a model for annual operation and maintenance costs based on statistical surveys and analyses in 1991, 1994 and 1997. The model includes a large re-investment after the 10th operational year of 20% of the cost of the wind turbine. This re-investment is distributed over the operational years 11 to 20. See table 6.

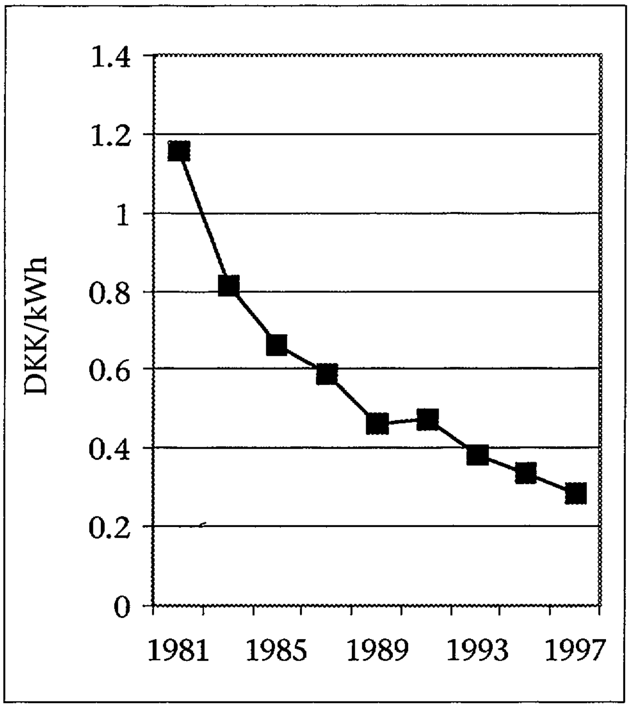


Figure 8. Estimated costs of wind generated electricity. Based on 20 years' depreciation, 5% interests rates and siting in roughness class 1 (A=5.6 and k=1.74). For actual siting see chapter 7.

Table 6. Annual operational and maintenance costs in % of the investment in the wind turbine. Source: Risø National Laboratory.

Machine size	150 kW	300 kW	5 - 600 kW
Year 1 - 2	1.2	1.0	1.0
Year 3 - 5	2.8	2.2	1.9
Year 6 - 10	3.3	2.6	2.2
Year 11 - 15	6.1	4.0	3.5
Year 16 - 20	7.0	5.0	4.5

5.3 Cost of Offshore Projects

In 1991 Elkraft inaugurated the Vindeby offshore wind farm which had 11 Bonus 450 kW turbines. Today, the farm is owned and operated by the electricity utility, SEAS. The total cost of this project was DKK 66 million, excluding extraordinary costs such as the R&D-part of the project, investigation of the impact on fish etc. Annual production is estimated at 12,000 GWh and operation and maintenance cost amounted to DKK 0.0686/kWh.

In 1995 Midtkraft in the Elsam area installed a 5 MW wind farm at Tunø Knob, consisting of 10 Vestas 500 kW turbines. The total cost of this project was DKK 73.8 million, excluding such extraordinary costs as removal of mines, investigation of the impact on birds, etc. Annual production is estimated at 15,000 GWh and operation and maintenance costs amount to DKK 0.055/kWh.

A plan from July 1997 prepared by the two utility associations, Elkraft and Elsam, together with the Energy Agency and Environmental Protection Agency of the Ministry estimated the key figures for five offshore wind farms. See table. The report concludes that electricity production costs for these five wind farms are on the same level as those for turbines on less favourable sites on land.

5.4 Energy Balance

Several investigations have shown that the energy invested in production, installation, operation & maintenance and decommissioning of a typical wind turbine has a "pay-back" time (energy balance) of less than one year of operation. According to the Danish Wind Turbine Manufacturers' Association, manufacturing a state-of-the-art 600 kW wind turbine takes 3.2 TJ. taking into account everything from producing raw material to installing a finished machine and including 20 years of operation

Table 7. Key figures for five planned offshore wind farms. Production costs based on 20 years' depreciation, 5% interest rate and DKK 0.08/kWh in service and maintenance costs. 97 % availability and 2.5 % grid loss are assumed. Water depth 3.9 m to 8.6 m. January 1997 price level.

Key figures	Unit	Gedser	Rødsand	Omø	Læsø	Horns Rev
Installed capacity	MW	144	144	144	117	120
Net full load hours	Hours/year	3287	3330	3014	3380	3530
Investment	MDKK/MW	12.4	11.5	11.0	11.7	11.7
Production cost	DKK/kWh	0.38	0.36	0.37	0.36	0.35
Cost breakdown						
Turbines	MDKK	850	850	850	700	720
Foundations	MDKK	270	270	270	220	225
Grid connection and reinforcement	MDKK	440	310	230	240	250
Others	MDKK	230	230	230	205	205
Total	MDKK	1790	1660	1580	1365	1400

and maintenance and decommissioning. In suitable locations, the wind turbine will generate 1.1 to 1.3 million kWh per year in its projected 20-year useful life. The energy invested in a state-of-the-art 600 kW wind turbine is, therefore, repaid over 3-4 months.

6 The Impact of Wind Turbines on the Environment

Utilising wind power is one of the cheapest methods of reducing CO_2 emissions from electricity production. According to a Danish study, a 100 MW offshore wind farm will reduce CO_2 emissions by almost 0.3 million tons per year, when substituting power from conventional coal-fired power plants. The costs will be approximately USD 5 per ton of CO_2 for offshore wind farms situated near the coast.

The nuisance caused by turbine noise is one of the important limitations on siting wind turbines close to inhabited areas. Although modern wind turbines fulfil current regulations concerning noise, their size alone means that it is not appropriate to install them too close to inhabited areas. As there are very few open areas in Denmark without dwellings, utilising the open sea has great advantages.

The possible impact on wildlife is often an important matter in the public discussion. Danish studies of land-based wind farms conclude that wind turbines do not pose any substantial threat to birds and other wildlife. All of the appointed areas for offshore wind farms lie outside of EU bird sanctuaries but there are also important areas for birds in several of the sites. Studies have already been conducted of possible impact on sea birds at the Tunø Knob installation. The studies reveal that the eider has not been frightened away from the Tunø Knob area by the establishment of an offshore wind farm. The eider ducks that winter there are much more influenced by the presence of food than by the presence of the wind turbines. For the common scoter, the studies were inconclusive due to the relatively small number present.

6.1 External Costs

A European research project has established a comprehensive and comparable set of data on external costs of different power generation technologies. In the Danish National Implementation Project, the external costs of wind power are compared with other energy technologies[8]. Offshore and land-based wind farms have been compared with combined heat and power (CHP) plants fuelled with natural gas and biogas. All plants are situated in Denmark.

Table 8. External costs of offshore and land-based wind farms compared with combined heat and power (CHP) plants fuelled with natural gas and biogas. Source: L. Schleisner and P. S. Nielsen, External Costs Related to Power Production Technologies, Risø-R-1033(EN), December 1997.

Technology	External Costs mECU/kWh
Offshore wind farm	0.67 – 3.65
Land-based wind farm	0.59 – 2.55
Natural gas CHP plant (el)	7.11 – 80.00
Natural gas CHP plant (heat)	1.87 – 18.50
Biogas CHP plant (el)	4.36 – 16.12
Biogas CHP plant (heat)	1.32 – 4.57

The life-cycle analysis of a wind farm includes resource extraction, resource transportation, materials processing, component manufacture, component transport, turbine construction, decommissioning and turbine product disposal. Atmospheric emissions from the production of the wind turbines have a major impact on the total external costs for wind farms. Accidents involving the public as well as occupational health play a minor role. Impact from noise and visual amenity is very small for offshore wind farms, but larger for the land-based ones.

7 Wind Resources

Denmark has one of the best climates in Europe for utilising wind for power production. Only countries with a coastline direct to the Atlantic Ocean have better conditions in general. Wind energy could, in theory, provide more energy than is consumed in Denmark today. However, economic viability and siting difficulties limit this vast theoretical potential.

The wind resources in Denmark that can be utilised are partly on land and partly offshore in Danish waters.

As Denmark is a relatively densely populated country, Danish land-based wind resources are limited primarily by zoning restrictions and the balance between wind-energy development and other claims or interests in the open land.

The Danish Energy Agency has analysed the results of local planning, and on this basis has estimated the land-based wind energy potential at between 1,500 MW and 2,600 MW. It is estimated that 1,500 MW of installed wind-turbine capacity can produce 10 - 12 % of the electricity consumption in Denmark.

Scarcity of available land-based sites has led to the belief that wind turbines must be located on less and less favourable sites. The best sites were often developed first, leaving only inland sites with moderate wind conditions for new machines. So far statistics do not support this point of view. On average, over the last 10 years wind turbines have been sited in roughness class 1.47 (referring to the Beldringe data in the European Wind Atlas). This corresponds to an average annual wind speed at a height of 50 meter of 6.6 m/s (or 4.7 m/s in 10 meter). The trend during the period is flat indicating that good sites are still available. This is partly due to better micrositing of the turbines, as the wind resource assessment tools and the knowledge of how to use them have improved. See figure 9.

Several investigations of the offshore wind resources have been conducted since 1977 resulting in the finalisation of two demonstration projects. In July 1997 a plan of action for offshore wind farms was submitted to the Minister of Environment and Energy. The plan was drawn up by the two electricity utility associations, Elkraft and Elsam, together with the Energy Agency and the Environmental Protection Agency of the Ministry. The plan of action includes eight areas with water depths of up to 15 metres. The total theoretical installed capacity of these areas is 28,000 MW, 12,000 MW of which can realistically be utilised. Based on this, 4000 MW has been planned. The wind speeds in the areas allow 3530 "net-full load hours" in the North Sea (Horns Rev) and between 3000 and 3300 hours in interior Danish waters. (Hub height of 55 m and rotor diameter of 64 m are anticipated). This corresponds to an annual electricity production of 12 - 14 TWh. For comparison, total Danish electricity consumption in 1997 was 32 TWh.

8 Wind-Turbine Technology

8.1 Generations of Technology

Wind-turbine technology has developed dramatically in the period between the late 1970s and today. A large variety of machines has been produced and sold during the last 20 years.

The first generation of industrially produced turbines was based on a 5 meter blade such as the blade produced by "Økær Vind-Energi". The turbines had rotor diameters of 10 to 11 meters and they were equipped with a 22 kW or a 30 kW generator. Machines from this generation were primarily sold from 1978 to 1981.

The second generation started with the very popular 55 kW turbine, which had a 15 meter rotor and was upscaled to a 75 kW machine with a 17 meter rotor. This generation was developed in the late 1970s and the first versions were designed with a 45 kW generator, but only very few of these early 45 kW versions were actually sold. The second generation of turbines was based on a 7.5 meter blade from the 'Alternegy' company, and it dominated the Danish and the international wind-turbine market in the first half of the 1980s. Vestas started producing its own blades from the 7.5 meter generation.

The third generation consisted of turbines based on the 9 meter blade with generators in the range of 90 to 100 kW. Rotor diameter was between 18 to 20 metres. From this generation, LM Glasfiber A/S has dominated blade manufacturing together with Vestas, which produced blades for its own machines. For private wind-turbine owners, the maximum permitted machine size was limited to less than 100 kW in the late 1980s. That is why several manufacturers sold 95 kW and 99 kW machines during these years. The sales of this generation peaked in 1987.

The fourth generation of Danish wind turbines covers a range of turbines between 150 and 250 kW and was based on 11 and 12 meter blades. This size range dominated the market from the late 1980s to the early 1990s. The 150 kW machines (23 – 25 meter rotor diameter) and the 200 – 250 kW machines (25 – 29 meter rotor diameter) have been among the best selling wind turbines over the years.

An intermediate fifth generation of machines covers 300 kW and 400 kW with a rotor diameter of 30 – 31 metres and was based on 13 and 14 meter blades. The fifth generation started in the late 1980s with the early Bonus 450 kW machines, which had a rotor diameter of 35 metres. This generation gathered pace with the 500 kW machines with 37 to 39 metres in the early 1990s. During the mid 1990s, this generation was upcaled to 600 kW with rotor diameters of 43 and 44 metres.

Based on the fifth generation, an intermediate size range (a sixth generation) has been developed between the 500/600 kW and the MW size turbines. These are machines of 600 kW, 660 kW, 750 kW and 800 kW generators and 47 to 50 meter rotor diameter.

A seventh generation comprises the MW generation of turbines. This generation is partly the result of the European WEGA R&D programme. The first Danish prototype machines were installed by Danish utilities. These are machines in the range of 1000 kW to 1650 kW with rotor diameters of 54 to 66 metres. The size of this generation is expected to increase to about 2 MW. Very few machines of this generation have been sold in Denmark but several have been exported. See figure 10.

8.2 Increase in Size and Productivity

Average generator size has increased from 35 kW in 1981 to near 600 kW in 1997. The development in productivity of the turbines is often used as a technology indicator. The productivity is measured as annual electricity production divided by the rotor area of the machine. This productivity increased from less than 500 kWh/m^2 to near 1000 kWh/m^2 between 1981 to 1997. This development is a result of improved technology (including better micro-siting methodologies) and higher hub heights. See figure 11 and 12.

Table 9. Wind resources in Denmark.

	Planned capacity	Planned production	% of annual electricity consumption in 1997
On land	1,500 MW	3.3 TWh	10 – 12 %
Offshore	4,000 MW	12 - 14 TWh	~ 40 %

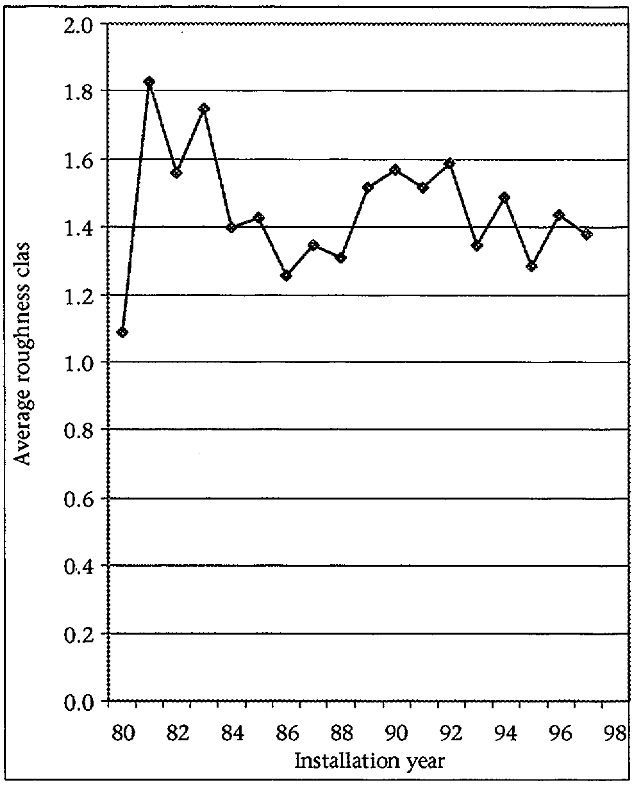


Figure 9. Average roughness class of sites by year of installation. The term "roughness class" refers to the Beldringe data in the European Wind Atlas. For 10 meter height and roughness class 1: A=5.6 m/s and k=1.74, for roughness class 2: A=4.9 m/s and k=1.74.

8.3 Reduced Noise Emission

Apart from cost reduction and improvement of reliability, the reduction of the noise emission from wind turbines has been the most important issue for technological development. As a rule of thumb, noise emission from wind turbines increases with increased turbine size. Compared with earlier technology, noise emission from modern turbines increases less steeply in relation to size. This indicates that new turbines are relatively less noisy that older ones. See figure 13.

8.4 Cheaper Wind Turbines

The ex-factory price of wind turbines of the fourth generation (1991, 150 kW - 225 kW) to the sixth generation (1997, 600 kW) level has decreased by 20% (measured in DKK/kW). Other investment costs related to a wind farm (foundation, grid connection, roads, consulting, etc.) have decreased 50% (from 28% to 20% of total investment), and electricity production costs have decreased by approximately 30%. Because 1) technological development and 2) manufacturing improvements have taken place together with 3) an up-scaling of the machines and an 4) increase of the market volume, it is difficult to de-

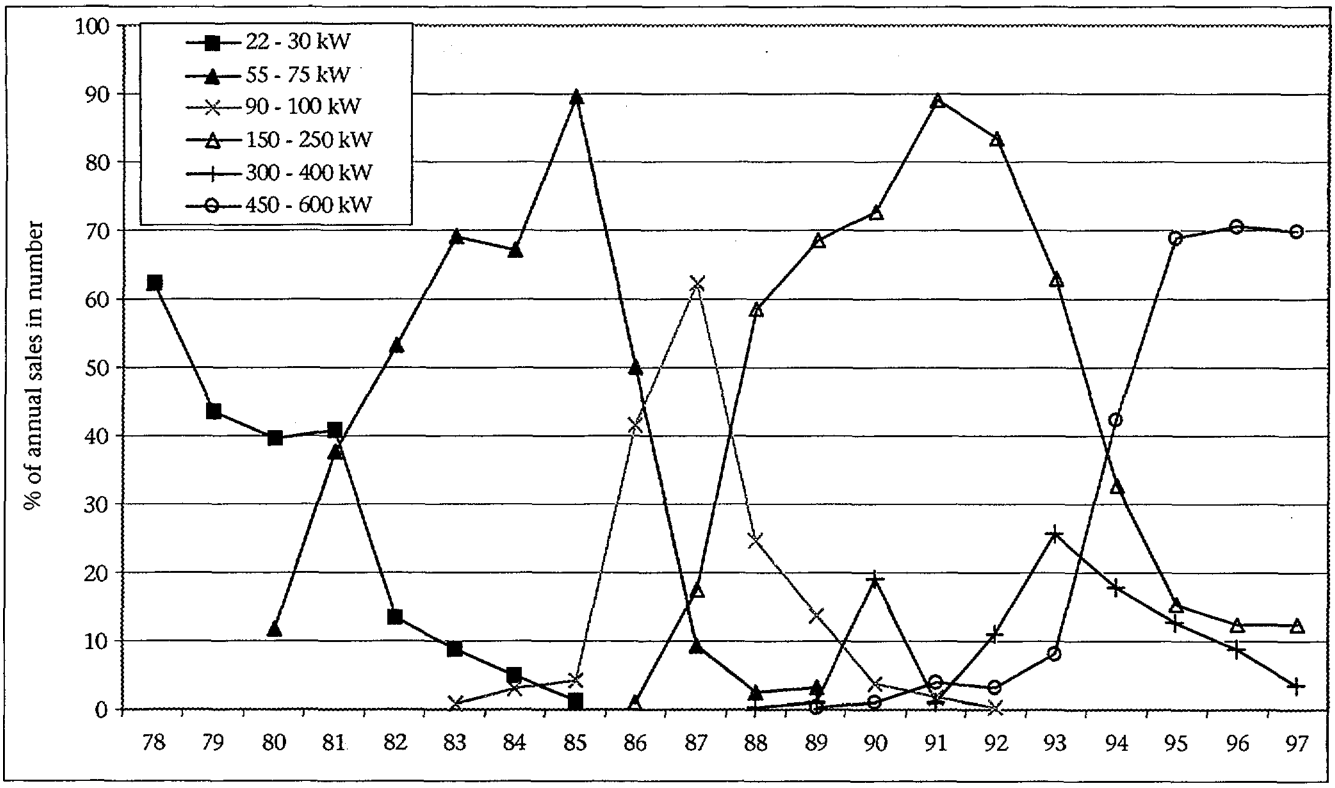


Figure 10. Market share of six generations of wind turbine technology. Source: E&M Data. Energi- & Miljødata for the Danish Energy Agency.

termine from which of these four sources cost reduction comes. As is generally acknowledged, the introduction of a new generation (or size) reduced turbine prices significantly - especially for the 600 kW generation. See figure 15 and 16.

8.5 Manufacturing and Quality

Over the last 20 years, the manufacturing of commercial ind turbines has become increasingly more industrialised. The increased volume in each manufacturing company has affected "economies of scale". Development and design of blades and machines increasingly includes manufacturability (as well as transport and installation) from the drawing board. Because of the Danish certification and type-approval scheme, all Danish wind turbine manufacturers have implemented quality assurance systems (the ISO9000 system), and their suppliers' qualifications have been up-graded accordingly.

8.6 Improved Resource Assessment Tools

Resource assessment tools have also improved over the years. Electricity production from wind turbines in a typical Danish landscape can be predicted quite accurately. Since the beginning of the 1980s, wind turbines on average have produced 3% more than predicted. See figure 14.

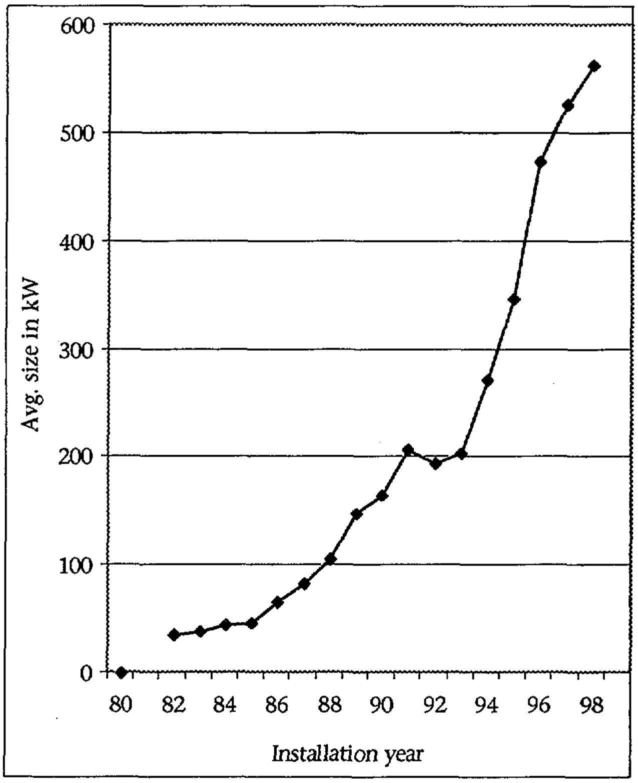


Figure 11. Average size of turbines increased from less than 50 kW in the early 1980s to near 600 kW in 1997. Source Energi & Miljø Data for the Danish Energy Agency.

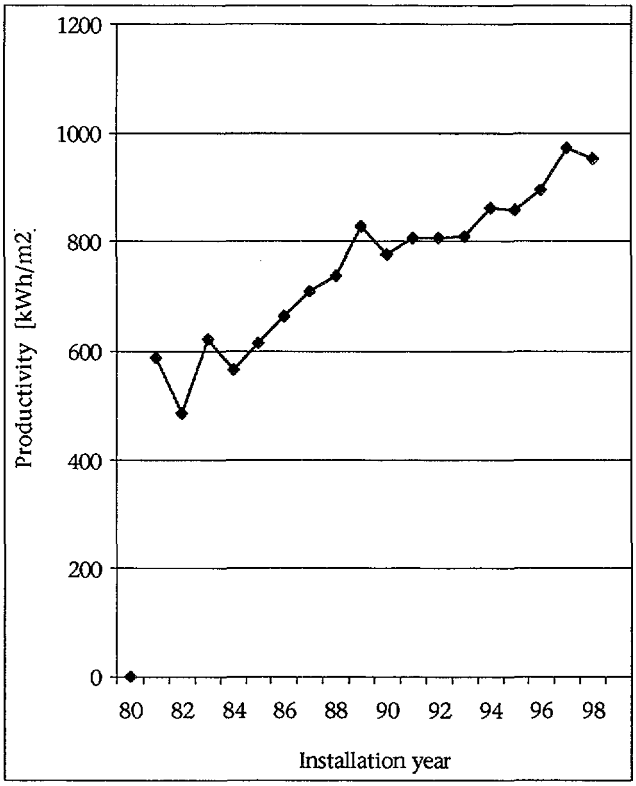


Figure 12. Productivity of wind turbines in kWh per m² swept rotor area. Electricity production has been normalised to a "normal wind year". Source Energi & Miljø Data for the Danish Energy Agency.

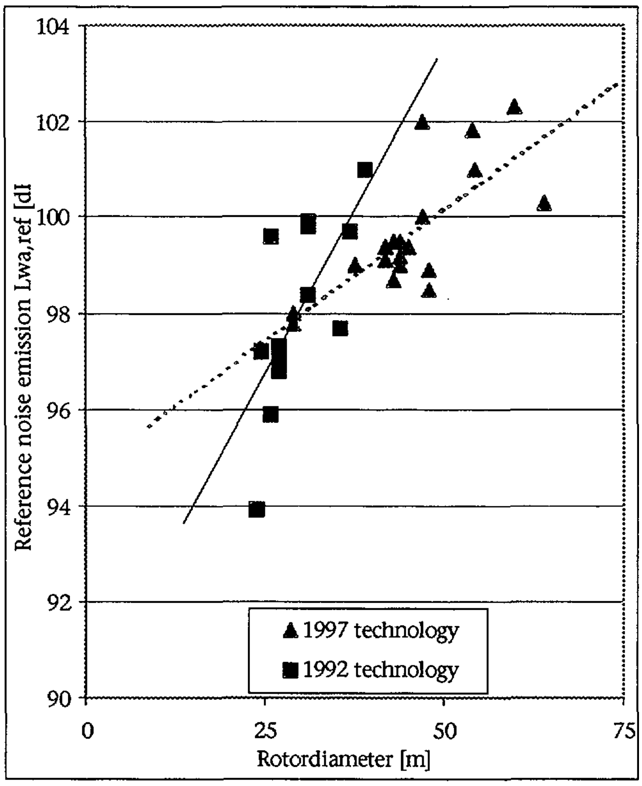


Figure 13. Comparison of reference noise emission ($L_{WA,ref}$) from turbines available on the market in 1992 and in 1997. The flatter trend for the 1997 technology indicates that modern, large wind turbines have relatively lower noise emission than older ones. Source: Vindmølleoversigten 1992 and 1997.

9 Industry and Services

Denmark has a large wind-turbine industry with a widespread net of Danish and international vendors. Danish-based manufacturers of large commercial wind turbines in the 150 kW to 1,650 kW range are: Bonus Energy A/S, NEG Micon A/S, Nordex Balke-Dürr GmbH, Vestas Wind Systems A/S, Wind World af 1997 A/S, Wincon (Vestfrost A/S). In addition, two companies produce smaller turbines in the 5 kW to 25 kW range: Gaia Wind Energy A/S and Calorius-Westrup A/S.

In 1995 the owners of Nordex A/S sold 51% of the shares to Balcke-Dürr AG. A new company is named Nordex Balke-Dürr GmbH. In 1997 the Nordtank Energy Group A/S and Micon A/S merged and formed the company NEG Micon A/S. After this merger, NEG Micon A/S acquired a number of other companies: the controller manufacturer, Danish DanControl A/S, the British blade manufacturer, Taywood Aerolaminates Ltd., and three wind-turbine manufacturers: the British Wind Energy Group, the Dutch NedWind, and the Danish Wind World of 1997 A/S.

The shares of Vestas Wind Systems A/S and NEG Micon A/S are listed on the Copenhagen Stock Exchange.

A number of industrial enterprises have developed important businesses as suppliers of major components for wind turbines. LM Glasfiber A/S is a world leading producer of fibre glass blades for wind turbines; Mita Teknik A/S and KK Electronic A/S produce controllers and communication systems; and Svendborg Brakes A/S is a leading supplier of mechanical braking systems. In addition, Danish subsidiaries of large international industries such as Siemens, ABB, SKF, FAG, etc. have developed businesses in the wind-power industry.

Service and maintenance of the more than 4,800 wind turbines in Denmark is carried out by the manufacturers' service departments, but a number of independent service companies have also been established. These include companies such as DWP Mølleservice A/S and DanService A/S.

Other industrial service enterprises have created important businesses in servicing the wind-power industry, for example companies that specialise in providing cranes for installation of wind turbines and providing transport of turbines, towers and blades, insurance services, etc. The major Danish consultancies on wind energy utilisation are BTM Consult Aps, E&M Data, ELSAMPROJEKT A/S, WEA Aps and Tripod Aps. There is one major independent developer of wind farms in Denmark, Jysk Vindkraft A/S, which sells turnkey projects to farmers and co-operatives. For type approvals, certifications, and test services see paragraph 3.8.1.

According to their association, the wind-turbine manufacturers had a turnover of more than DKK 5 billion in 1997. Total production in Denmark was 967 MW of

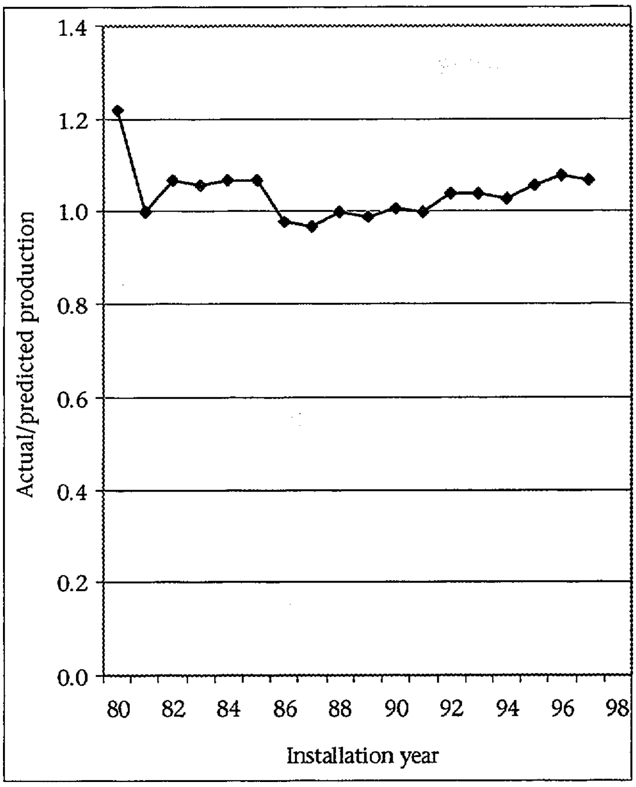


Figure 14. Development in the ability to predict annual electricity production. Average over the years is a 3% deviation between predicted and actual production. Source: Energi & Miljø Data for the Danish Energy Agency.

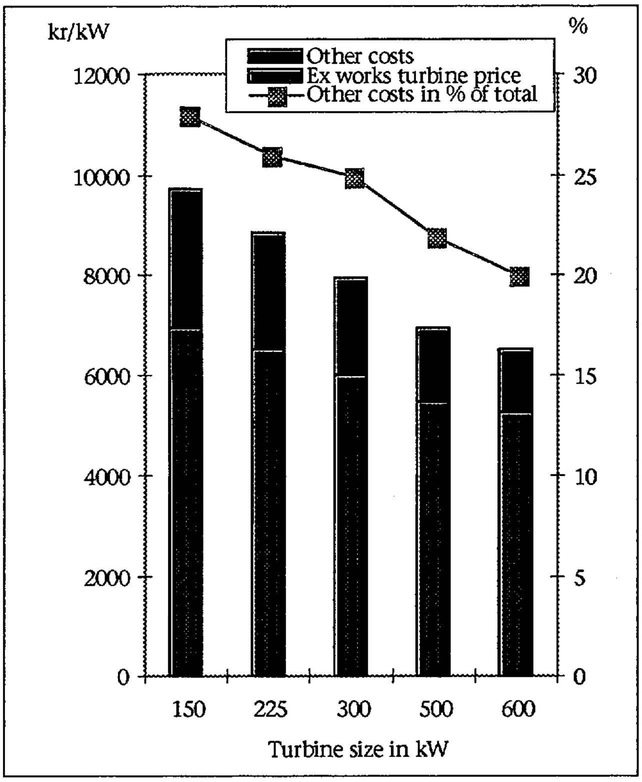


Figure 15. Development of installation costs for different generations and sizes of machines. Price level 1996. Based on statistical analyses. Source: Risø National Laboratory.

which 286 MW was sold domestically and 257 MW in Germany. Other large markets are Spain (133 MW), China (74 MW), Ireland (55 MW) and Great Britain (43 MW). Increasingly more production takes place in foreign subsidiaries and joint-ventures. Danish wind-turbine manufacturers employed 2,150 workers by the end of 1997. An additional 10,000 are estimated to be employed domestically by suppliers and business services of the industry.

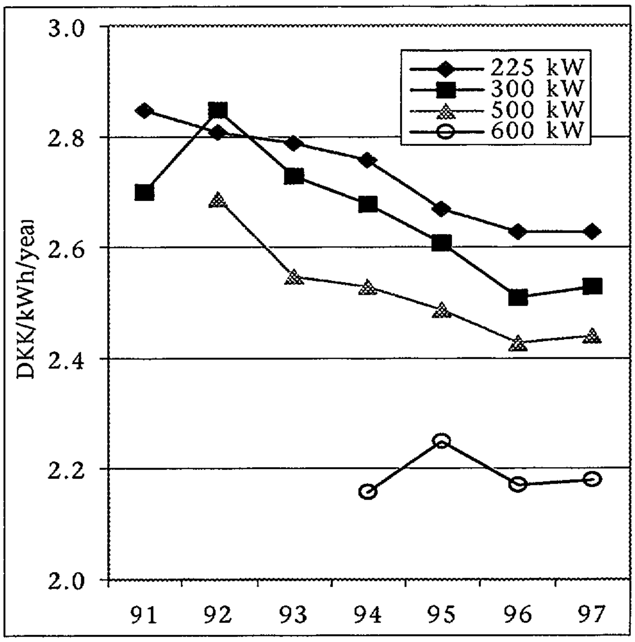


Figure 16. Development of specific investment defined as ex-works turbine price divided by annual production in roughness class 1. Price level 1996. Based on list prices of leading manufacturers.

10 International Programmes

Danish aid programmes and international parts of environment and energy research and development programmes have been used to stimulate wind-energy development in developing countries. The Danish Environmental Protection Agency under the Ministry of Environment and Energy runs the DANCED (Danish Cooperation for Environment and Development) programme. The DANCED organisation has been involved in projects in Asia and Southern Africa. Some of these projects also comprise clean energy technologies such as wind energy.

Wind turbines and wind-turbine technology have been included in bilateral aid projects under DANIDA, the Danish Ministry for Development. Small demonstration projects have been established in countries such as Cape Verde, Egypt and India. Transfer of wind technology and manufacturing capability have been important elements in aid projects in, for example, India and Egypt. Like its sister organisations in the USA, the UK, France, Germany, Sweden, etc. DANIDA also runs a mixed-credit programme. A Danish mixed credit is partially tied to interest-free or low interest loans with from 8 to 15 year maturity, aimed at financing development projects executed by Danish exporters in creditworthy developing countries. Mixed credits may be granted to creditworthy developing countries on the OECD's Development Committee's List for Developing Countries. The granting of such subsidised credits is regulated by the OECD Consensus Agreement on Export Credits. The rules imply that tied-aid credits should *"provide needed external resources to countries, sectors or projects with little or no access to market financing"*.

Appendix Statistical Tables

Table A1. Annual installed turbines in numbers and capacity distributed by ownership. Source: Energi- og MiljøData, Aalborg. Figures are based on manufacturers' sales and corrected for decommissioned turbines.

	Others		Utilities		Individuals		Cooperatives		Total	
Year	Number	MW	Number	MW	Number	MW	Number	MW	Number	MW
78	1	1.0		0.0	7	0.1		0.0	8	1.1
79	0	0.0	2	1.2	13	0.2	1	0.0	16	1.5
80	3	0.1	5	3.7	92	2.0	8	0.4	108	6.3
81	4	0.2		0.0	75	2.2	16	0.8	95	3.3
82	3	0.1		0.0	74	2.2	26	1.4	103	3.8
83	10	0.5		0.0	52	1.7	49	2.6	111	4.9
84	21	1.1		0.0	69	2.2	66	3.7	156	7.2
85	23	1.3		0.0	101	6.1	219	15.1	343	22.6
86	5	0.4		0.0	85	7.4	234	19.0	324	26.9
87	6	0.9		0.0	50	5.2	236	24.6	292	30.8
88	2	0.2	88	12.8	78	11.1	249	37.3	417	61.6
89	3	0.4	107	18.0	93	13.2	234	40.0	437	71.7
90	0	0.0	77	24.8	73	10.2	206	38.0	356	73.1
91	5	1.1	58	15.3	85	15.3	240	43.4	388	75.2
92	1	0.1	71	17.8	31	5.0	138	26.1	241	49.0
93	1	0.0	62	21.9	35	8.2	83	18.9	181	49.3
94	2	0.2	41	19.5	49	15.7	52	14.5	144	50.0
95	2	1.2	84	45.6	75	33.9	33	11.2	194	91.9
96	4	1.6	42	21.7	341	183.1	23	9.1	410	215.5
97	19	12.0	44	23.6	420	238.8	50	25.7	533	300.1
TOTAL	115	23.3	681	226.2	1898	564.6	2163	332.6	4.857	1146.8

Table A2. Stock of wind generating capacity (in numbers and MW) by the end of the year and annual production. Source: Association of Danish Electricity Utilities. Figures based on grid-connected turbines.

Year	Private No.	Utilities No.	Total No.	Private MW	Utilities MW	Total MW	Private GWh	Utilities GWh	Total GWh
78			8			1.2			
78			24			2.7			
80			132			9.0	0	0	
81			227			12.4	0	0	
82			330			16.3	0	0	
83	507	3	510	18	1.5	19.5	26	1	27
84	633	3	636	25.2	1.5	26.7	32	1	33
85	958	4	962	47	1.8	48.8	50	1	51
86	1311	9	1320	75.9	5.6	81.5	124	2	126
87	1623	8	1631	109.7	4.8	114.5	169	5	174
88	1907	181	2088	162.8	33.7	196.5	260	32	292
89	2255	302	2557	214.8	47.4	262.2	268	61	429
90	2537	352	2889	262.9	80.3	343.2	502	108	610
91	2847	396	3243	320.3	93.1	413.4	595	147	742
92	2999	443	3442	351.4	106.7	458.1	715	187	902
93	3080	468	3548	377.5	114.2	491.7	825	227	1052
94	3151	519	3670	399.1	138.7	537.8	842	241	1083
95	3240	590	3830	439	180	61.	889	285	1174
96	3613	637	4250	639	203	842	912	315	1227
97	4112	672	4784	907	222	1129	1548	384	1932

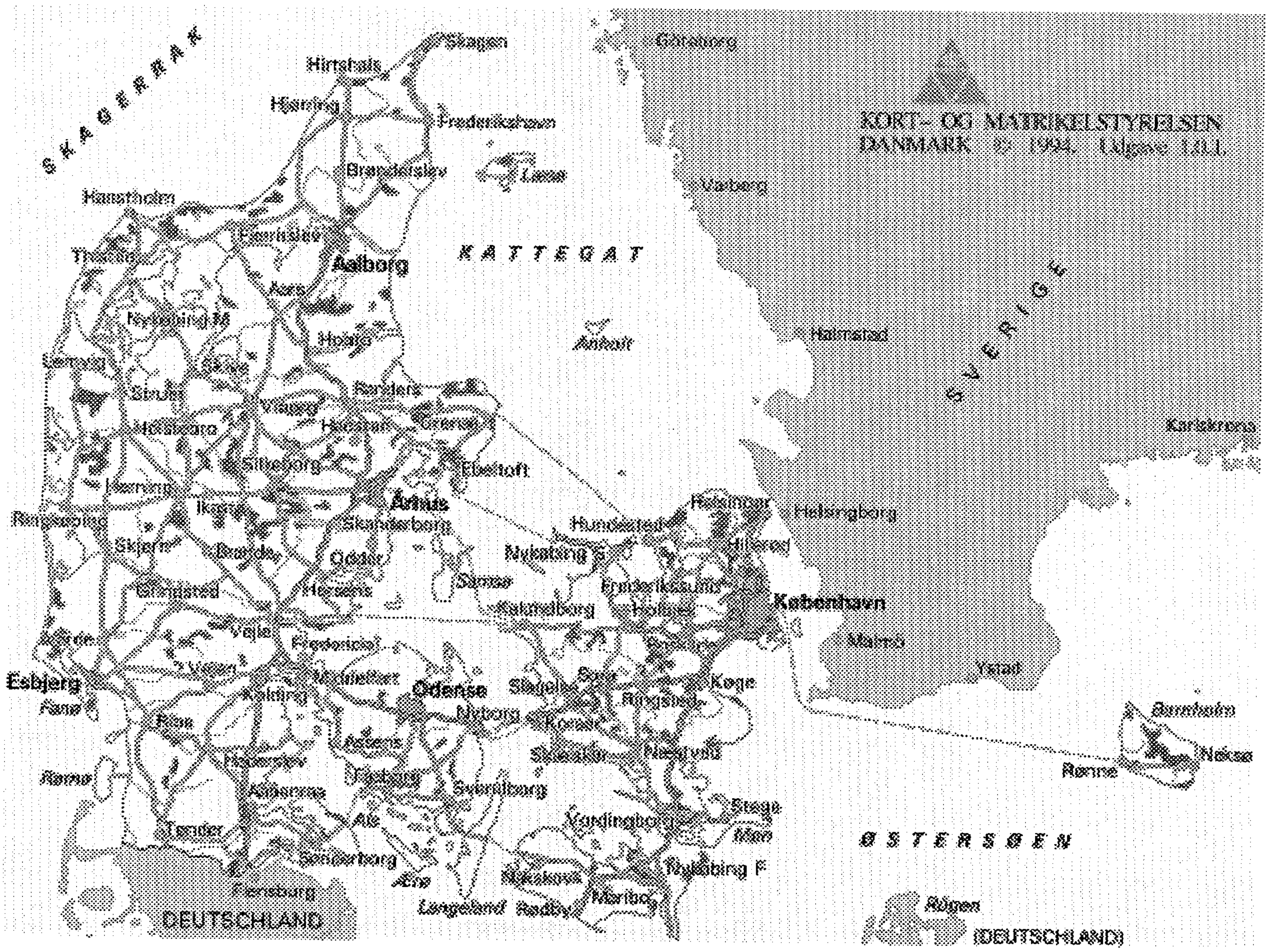
Table A3. Annual market share in percent of selected generations of turbines. Based on numbers of turbines. See chapter 8. Source: Energi- og Miljødata.

Year	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97
22-30 kW	62.5	43.8	39.8	41.1	13.6	9.0	5.1	1.5												
55-75 kW			12.0	37.9	53.4	69.4	67.3	89.8	50.3	9.6	2.6	3.4								
90-100 kW						0.9	3.2	4.4	41.7	62.3	24.9	14.0	3.9	2.1	0.4					
150-250 kW									0.9	17.5	58.5	68.4	72.8	88.9	83.4	63.0	32.6	15.5	12.4	12.4
300-450 kW											0.5	1.1	19.4	1.3	11.2	26.0	18.1	12.9	9.0	3.8
450-600 kW												0.5	1.1	4.1	3.3	8.3	42.4	69.1	70.7	70.0

Table A4. Characteristics of added turbines year by year. See chapters 7 and 8. Source: Energi- og Miljødata.

Year	Goodness of prediction	Avg. roughness class	Production per swept rotor area	Production per generator capacity	Number of turbines	Added capacity	Avg. size
			kWh/m2	kWh/kW		MW	kW
80	1.22	1.09	586	1897			
81	1.00	1.83	485	1666	95	3	35
82	1.07	1.56	621	2033	103	4	38
83	1.06	1.75	564	1917	111	5	45
84	1.07	1.40	614	2129	156	7	46
85	1.07	1.43	664	2134	343	23	66
86	0.98	1.26	709	2225	324	27	83
87	0.97	1.35	736	2191	292	31	106
88	1.00	1.31	828	2120	417	62	148
89	0.99	1.52	775	2086	437	72	164
90	1.01	1.57	806	2265	356	73	205
91	1.00	1.52	807	2356	388	75	194
92	1.04	1.59	809	2335	241	49	204
93	1.04	1.35	861	2183	181	49	273
94	1.03	1.49	861	2184	144	50	348
95	1.06	1.29	895	2219	194	92	474
96	1.08	1.44	973	2387	410	216	526
97	1.07	1.38	956	2340	533	300	563

General Information bout Denmark 1997



Geography

Area:	43,094	km²
Coastline:	7,314	km
Number of islands:	405	
Number of lakes:	1,008	
Forest area:	4,450	km²
Preserved areas:	1973	km²

Climate

Average temperature (1961-1990)

January:	0 °C	
July:	15.6 °C	
Sunshine (average per year):	1,670	hours
Degree days on average:	3,175	

Population

Population:	5.2	million
Population density:	122	per km²

Economics

GNP:	DKK	1,014	billion
Exports:	DKK	351	billion
Imports:	DKK	306	

Currency

1 krone (DKK) = 100 øre
1 USD (Oct. 1997) = 6.69 DKK
1 DEM (Oct. 1997) = 3.81 DKK
1 GBP (Oct. 1997) = 10.92 DKK